

# Atmospheric Optical Depth Retrieval from Multiangle Chris Images

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## Abstract

The interaction of the atmosphere with the solar radiation reflected from the Earth's surface heavily affects the remotely sensed images acquired by passive optical sensors. In order to obtain unbiased estimations of the surface reflectance, the above image degradation and radiometric distortion of the acquired data must be corrected, an operation which is called "atmospheric correction" often. Knowing the local parameters of the Earth atmosphere is therefore necessary for performing any atmospheric correction procedure, moreover this knowledge also is important for many environmental studies and remote sensing applications. In this paper a direct method of estimating the atmospheric optical depth (direct transmittance) using images acquired by the sensor CHRIS is discussed. The estimation of the optical depth is possible since this instrument is able to acquire up to five overlapping images of the same ground location observed under different sightlines. In such a way, this method allows us to estimate the atmospheric optical depth for twelve spectral channels of the CHRIS spectrometer. Such estimates can be used either for an optimal tuning of the atmospheric correction algorithm or to assess the state of the atmosphere.

## Keywords

*Component; Optical Depth; Atmospheric Correction; Atmospheric Optics; Remote Sensing; CHRIS-PROBA*

## Introduction

For a long time the remotely sensed data acquired by passive optical sensors have been used for answering many questions in a wide range of disciplines that are concerned with land-surface processes (Asrar 1989). Such instruments are known to obtain Earth's surface images in several narrow bands in visible and infrared regions of the electromagnetic spectrum. This information allows us to state and solve the problem of the Earth's surface identification. The accuracy of such deductions is determined by many factors depending on both sensor characteristics and conditions of observation. One of the most important factors is the

influence of the atmosphere on the radiation collected by sensor. The interaction of the solar radiation reflected from the ground with the atmosphere hinders the quantitative use of the remotely sensed data, demanding for the atmospheric correction of the collected data. In its turn, this correction requires the knowledge of various atmospheric and signal parameters, which concur to determine the signal distortion caused by the atmosphere. The most straightforward solution to this problem is obtained when these parameters can be directly deduced from the remotely sensed data alone. In this case the interfering effect on the atmospheric parameter estimation originated by reflection / scattering phenomena taking place near the ground may be very strong. Nevertheless, in certain specific cases some atmospheric characteristics can be measured (estimated) from remotely sensed data. A successful example of such estimation is the atmospheric correction of the ocean color, where the very low reflectance of the water in the red region of the visible spectral range can be used for the atmospheric correction (Gordon 1978). A number of papers and research works have been devoted to the estimation of atmospheric optical parameters and the atmospheric correction of remotely sensed images (Liang et al. 2001, Kaufman 1984, Lyapustin 2001, Thome et al. 1998, Kaufman et al. 1997, Davis et al. 2010, Karpouzli and Malthus 2003, Wen et al. 1999, Barducci et al. 2008, Semenov et al. 2011).

The estimation of the atmospheric characteristics relying on inverse modeling of remotely sensed data only is the preferable practice because it doesn't require any additional equipment, and permits to recover correct information from past acquisitions. However, it should be emphasized that these estimates can be obtained only for images having specific properties in terms of observed materials and sensor's characteristics, and that the accuracy of such estimates

cannot be reliably controlled always. Let us note that most remote sensing instruments are designed for Earth observation, not for the measurement of atmospheric features. Nevertheless, such estimates are a possible source of additional and sometime unique information about the local state of the atmosphere.

In this paper we discuss a direct method for assessing the atmospheric optical depth, i.e. the direct transmittance, which adopts the remotely sensed data only. The paper is organized as follows. Section II introduces the basic method for estimating the atmospheric optical depth stemming from remotely sensed images acquired under two angles of observation, and shows its limitation. The extension of this method to images acquired from five view points, as in a case of CHRIS/PROBA is also addressed. Section III shows the results of atmospheric optical depth estimation obtained from natural images in 12 spectral channels of the imaging spectrometer CHRIS-PROBA. The last section draws some conclusions.

### Estimation of Atmospheric Optical Depth

Our method of estimating the atmospheric optical depth  $\tau$ , or the direct transmittance  $T = e^{-\tau}$ , is based on the comparison between the two values of the radiance variance averaged over all the pixels of the same area in the two images received at two different observation angles (Semenov 2002, Moshkov et al. 2009).

#### Estimation of Atmospheric Optical Depth Using Images Acquired from Two Observation Angles

Suppose we have two images of the same ground location acquired under the observation angles  $\vartheta_1$  and  $\vartheta_2$  in the same spectral channel of a passive optical sensor. Without loss of generality we can assume  $\vartheta_1 = 0$  and  $\vartheta_2 = \vartheta$ , so one image corresponds to the nadir viewing geometry.

The radiance of an arbitrarily resolved pixel of the image gathered over the nadir direction can be written as

$$b_i^{(0)} = b_A^{(0)} + B_i^{(0)} e^{-\tau} \quad i = 1, 2, \dots, N$$

where  $b_A^{(0)}$  is the atmospheric path radiance not reflected from the surface,  $B_i^{(0)}$  is the radiance of the  $i^{\text{th}}$  resolved element on the surface observed in nadir, and  $N$  is the number of pixels in the image. Here, we assume the image have been preliminary corrected to remove the scattering contribution to radiance (the so-

called "adjacency effect", Semenov et al. 2011). Moreover, we assume that the image size (i.e. the sensor FOV) is small enough that possible variations of the optical depth along the sightline corresponding to different pixels can be disregarded.

When observing the same resolved ground location from the slant sightline  $\vartheta$  we obtain the radiance stated by the following equation:

$$b_i^{(\vartheta)} = b_A^{(\vartheta)} + B_i^{(\vartheta)} e^{-\mu\tau} \quad i = 1, 2, \dots, N$$

where  $b_A^{(\vartheta)}$  and  $B_i^{(\vartheta)}$  are the atmospheric path radiance, and the radiance emitted by the resolved element observed at the angle  $\vartheta$ , the air-mass parameter being represented by  $\mu = 1/\cos \vartheta$ .

The variance of the radiance image seen in the nadir direction can be determined as

$$\hat{S}(0) = \frac{1}{N} \sum_{i=1}^N [b_i^{(0)} - m^{(0)}]^2$$

where  $m^{(0)} = \frac{1}{N} \sum_{i=1}^N b_i^{(0)}$  is the average for the nadir image. Similarly, the radiance variance for the image at the angle  $\vartheta$  can be calculated as:

$$\hat{S}(\vartheta) = \frac{1}{N} \sum_{i=1}^N [b_i^{(\vartheta)} - m^{(\vartheta)}]^2$$

where  $m^{(\vartheta)} = \frac{1}{N} \sum_{i=1}^N b_i^{(\vartheta)}$  is the image average corresponding to the observation angle  $\vartheta$ . The estimated atmospheric optical depth  $\hat{\tau}$  can then be defined as shown in the next equation:

$$\hat{\tau}(\vartheta) = -\frac{1}{2k(\vartheta)} \ln \left( \frac{\hat{S}(\vartheta)}{\hat{S}(0)} \right)$$

And  $k(\vartheta) = \mu - 1$ .

Let's now consider the errors of the estimate (5). Evidently, the radiance of an arbitrarily resolved element of the image at the angle  $\vartheta$  can be written as:

$$b_i^{(\vartheta)} = b_A^{(\vartheta)} + [B_i^{(0)} + \beta_i^{(\vartheta)}] e^{-\mu\tau}, \quad i = 1, 2, \dots, N$$

where  $\beta_i^{(\vartheta)}$  is the difference of emitted radiance for the  $i^{\text{th}}$  pixel between the two viewing directions  $\vartheta$  and 0. The image average of the radiances coming from the two datasets (view-lines) yields:

$$\begin{aligned} m^{(0)} &= b_A^{(0)} + M^{(0)} e^{-\tau} \\ m^{(\vartheta)} &= b_A^{(\vartheta)} + M^{(0)} e^{-\mu\tau} + \Delta M^{(\vartheta)} e^{-\mu\tau} \end{aligned}$$

where  $M^{(0)} = \frac{1}{N} \sum_{i=1}^N B_i^{(0)}$  is the mean emitted radiance for the image observed in the nadir direction

(neglecting the atmospheric attenuation), and  $\Delta M^{(g)} = \frac{1}{N} \sum_{i=1}^N \beta_i^{(g)}$  is the radiance deviation averaged over the image at the angle  $g$ . From (7) it is possible to compute the deviation  $\Delta b_i^{(g)}$  of the radiance emitted by a generic pixel from its image average, as shown in the equation below:

$$\begin{aligned}\Delta b_i^{(0)} &= b_i^{(0)} - m^{(0)} = \Delta B_i^{(0)} e^{-\tau} \\ \Delta b_i^{(g)} &= b_i^{(g)} - m^{(g)} = \Delta B_i^{(0)} e^{-\mu\tau} + \Delta \beta_i^{(g)} e^{-\mu\tau}\end{aligned}$$

where  $\Delta B_i^{(0)} = B_i^{(0)} - M^{(0)}$  and  $\Delta \beta_i^{(g)} = \beta_i^{(g)} - \Delta M^{(g)}$ . In view of (8), it is easy finding an expression for the radiance variance  $\hat{S}(g)$ :

$$\begin{aligned}\hat{S}(0) &= \frac{1}{N} \sum_{i=1}^N [\Delta B_i^{(0)}]^2 e^{-2\tau} \\ \hat{S}(g) &= \frac{1}{N} \sum_{i=1}^N [\Delta B_i^{(0)} + \Delta \beta_i^{(g)}]^2 e^{-2\mu\tau}\end{aligned}$$

Then the estimate of the atmospheric optical depth  $\hat{\tau}$  in (5) becomes:

$$\hat{\tau}(g) = -\frac{1}{2k(g)} \ln \left( \frac{\hat{S}(g)}{\hat{S}(0)} \right) = \tau + n_\tau$$

where

$$n_\tau = -\frac{1}{2k(g)} \ln \left\{ 1 + \frac{2 \sum_{i=1}^N \Delta B_i^{(0)} \Delta \beta_i^{(g)} + \sum_{i=1}^N [\Delta \beta_i^{(g)}]^2}{\sum_{i=1}^N [\Delta B_i^{(0)}]^2} \right\}$$

is the estimation error, and  $\tau$  is the true value of the atmospheric optical depth. Equation (11) just implies that in the case of a Lambertian field of reflectance ( $\Delta \beta_i^{(g)} = 0$ ) the estimate (10) equates the true value of the atmospheric optical depth, while any deviation of the reflectance of the observed scene from the behavior of a Lambertian surface gives rise to possible errors affecting  $\hat{\tau}$ . It should also be noted that equations from (5) to (11) have been obtained assuming the two images involved in calculations are exactly matched (co-registered), otherwise an additional error due to spatial mismatching arises.

The following conclusions can be derived from the analyses of the eq. (11).

- 1) For surfaces with fixed scattering properties the lesser is  $k(g)$  (the lesser is an angle of observation  $g$ ) the greater is the estimation error  $n_\tau$ .
- 2) The error  $n_\tau$  only depends on the centered value of the involved reflectance fields.

Therefore, if we assume  $\Delta B_i^{(0)}$  and  $\Delta \beta_i^{(g)}$  to be independent random variables, the sum  $\sum_{i=1}^N \Delta B_i^{(0)} \Delta \beta_i^{(g)}$  in (11) is zero, and the greater is the amplitude of  $\Delta B_i^{(0)}$  with respect to  $\Delta \beta_i^{(g)}$ , the lesser is the error. For a given  $\Delta \beta_i^{(g)}$ , an augment of  $\Delta B_i^{(0)}$  corresponds to an increase of the range of spatial variability along the image, i.e. increasing the variance of the image.

- 3) Since the angular scattering properties of the natural surfaces constituting the available images are unknown, we suppose that the estimation of the atmospheric optical depth  $\tau$  deduced from two different sight lines (images) only is prone to large errors.

### Estimation of Atmospheric Optical Depth Using CHRIS Images (Multiple Observation Angle)

A new generation of optical sensors has been developed in the last years. Such sensors are characterized by a large number of spectral channels, finer radiometric accuracy, lesser volume and mass budgets, and in some cases the ability to capture Earth's images of the same site for various angles of observation. A good example of such sensors is the Compact High Resolution Imaging Spectrometer (CHRIS) developed by the European Space Agency (ESA), and mounted onboard the compact satellite PROBA. CHRIS-PROBA operates over the visible and near infrared spectral region, from 400 nm up to 1050 nm. This spectral range is covered with 63 spectral bands at a Ground Sampling Distance (GSD) of 36 m, or with 18 bands at a spatial resolution of 18 m. The actual CHRIS spatial resolution is somewhat variable as its altitude varies from 553 km to 588 km. Using PROBA's angle steering capabilities in along and across track directions, sets of 5 images can be acquired for the selected site along the same orbit, at the following Fly-by Zenith Angles (FZA, along track) of  $+55.0^\circ$ ,  $+36.0^\circ$ ,  $0.0^\circ$ ,  $-36.0^\circ$ ,  $-55.0^\circ$ . Additional information regarding the CHRIS-PROBA characteristics and its acquisition modes can be found in Barducci et al. 2009. In order to adopt CHRIS-PROBA data for autonomous estimation of the atmospheric optical depth, we have further developed the optical depth estimation procedure. The resulting modeling is free from the limitations characteristic of the basic procedure described above that only uses images from two observation angles.

Let us suppose to have five matched images of the same area obtained in the same spectral channel for the five observation geometries typical of the CHRIS-PROBA sensor, indicated by angles  $\vartheta_0 = 0.0$ ,  $\vartheta_1 = 36.0$ ,  $\vartheta_2 = 55.0$ ,  $\vartheta_3 = -36.0$ , and  $\vartheta_4 = -55.0$ . Hence, we can compute four independent estimates of the atmospheric optical depth for the four non-null observation angles:

$$\hat{\tau}(\vartheta_j) = -\frac{1}{2k(\vartheta_j)} \ln \left( \frac{\hat{S}(\vartheta_j)}{\hat{S}(\vartheta_0)} \right) \quad j = 1, \dots, 4$$

The surfaces of targets framed in the available images will not have an exact Lambertian behavior, thus the various estimates  $\hat{\tau}(\vartheta_j)$  resulting from (12) will be mutually different, and each one of them will differ from the true value  $\tau$ . As long as the statistical properties of the measurement "noise" are unknown, it is appropriate to accept as optimal  $\tau$  estimation the value that minimizes the dispersion of the estimates (the standard deviation of the estimates). As known, the arithmetic mean is the estimator that obeys this property. However, considering the dependence reported in (11) of the estimation error on the observation angle, it seems desirable to adopt a weighted average of the estimates obtained in various viewing geometries. To this purpose, we consider the general weighted dispersion formula:

$$\sum_{j=1}^N \omega_j (\hat{\tau}_j - \hat{\tau}_m)^2$$

that is minimized by the following estimator:

$$\hat{\tau}_m = \frac{\sum_{j=1}^N \omega_j \hat{\tau}_j}{\sum_{j=1}^N \omega_j}$$

In view of (11) we choose the weights  $\omega_j = k^2(\vartheta_j)$ , which have the property  $k(\vartheta_1) = k(\vartheta_3)$  and  $k(\vartheta_2) = k(\vartheta_4)$ . In summing up, we can write:

$$\hat{\tau}_m = \frac{k^2(\vartheta_1)(\hat{\tau}_1 + \hat{\tau}_3) + k^2(\vartheta_2)(\hat{\tau}_2 + \hat{\tau}_4)}{2[k^2(\vartheta_1) + k^2(\vartheta_2)]}$$

Equation (15) holds true for an atmospheric optical depth retrieved from CHRIS-PROBA data, and is easily extended to the general case of  $N$  available viewing directions, i.e. (14). It is worth noting that the optical depth estimation involving data from multiple Point of Views (POVs) allows us to increase the accuracy of the final estimation, and even to control its quality. When observing an ideal Lambertian surface, any estimation

$\hat{\tau}(\vartheta_j)$  matches the actual value of  $\tau$ , and in the opposite circumstance  $\hat{\tau}(\vartheta_j) \neq \hat{\tau}(\vartheta_l) \quad \forall j \neq l$ . Therefore, the dispersion of the  $N$  available estimations is a measure of the quality of the average estimate in (14-15). We can define the following discrepancy function  $\hat{\varepsilon}$  which measures the quality of the inferred optical depth:

$$\hat{\varepsilon} = \sum_{j=1}^4 k^2(\vartheta_j) [\hat{\tau}_j - \hat{\tau}_m]^2$$

Let us note that a vanishing  $\hat{\varepsilon}$  is a necessary condition of an exact estimate  $\hat{\tau}(\vartheta_j) = \tau \quad \forall j$ , but it is not sufficient. This means that  $\hat{\tau}(\vartheta_j) = \tau \quad \forall j$  implies  $\hat{\varepsilon} = 0$ , but the converse is not necessarily true. For the specific case of the CHRIS-PROBA images, for which  $\vartheta_1 = -\vartheta_3$  and  $\vartheta_2 = -\vartheta_4$ , the estimation quality can also be characterized by the next expression that defines the discrepancy of means  $\hat{\varepsilon}_p$ :

$$\hat{\varepsilon}_p = \sum_{j=1}^2 k^2(\vartheta_j) [\hat{\tau}_{mj} - \hat{\tau}_m]^2$$

$$\hat{\tau}_{mj} = (\hat{\tau}_j + \hat{\tau}_{j+2})/2 \quad j = 1, 2$$

Unfortunately, as in a case of the ordinary discrepancy, zero discrepancy of means is a necessary but not at all sufficient condition for the equality between the estimate  $\hat{\tau}_m$  and the true value  $\tau$ . Let us note that  $\hat{\varepsilon}_p$  can be zero even for a non-lambertian surface, when  $\hat{\tau}_{ml} = \tau, l = 1, 2$ .

Since Lambert reflection is an idealization of a complex phenomenon, only rarely this behavior will account for all the targets of a whole scene. At the same time, most images contain a great number of different objects, both natural and artificial, with various scattering (reflecting) properties. Repeating the atmospheric optical depth estimation for a number of single image fragments significantly increases the probability to find an image fragment with quasi-Lambertian reflectance. The estimation performed for this fragment should be characterized by null or vanishing discrepancy, and we could select the minimal discrepancy estimation from the mess of estimations obtained in this way.

### Optical Depth Estimation for a CHRIS Dataset

The optical depth estimation procedure previously outlined has been applied to a CHRIS-PROBA dataset acquired over the San Rossore test site (Pisa, Italy), on the 16th of June 2003. For this acquisition, the CHRIS

spectrometer was operated in Mode 4, collecting data from 18 spectral bands at a GSD of 18 m. Unfortunately, the last six spectral channels of this and other CHRIS-PROBA acquisitions experienced significant calibration troubles (Barducci et al. 2009), a circumstance that hindered the option to retrieve significant optical depth estimations at these wavelengths. Validation data collected in-field gave the following results: temperature +28.50 C, relative humidity 65%, pressure 1011 mbar, integrated solar irradiance 810 w m<sup>-2</sup>, and diffuse solar irradiance 170 w m<sup>-2</sup> (both from 0.285  $\mu$ m – 2.800  $\mu$ m). Fig. 1 shows a true color composite of a mosaic of the five angular views provided by the CHRIS-PROBA imaging spectrometer.



FIG. 1 EXAMPLE OF CHRIS-PROBA ACQUISITION OVER THE SAN ROSSORE (PISA, ITALY) TEST SITE. THE CENTRAL IMAGE (TOP OF PICTURE) HAS BEEN GATHERED WITH ZERO FZA, THE TWO IMAGES ON THE CENTRAL REGION OF THE PICTURE HAVE FZA=±36° AND THE TWO BOTTOM IMAGES CORRESPOND TO FZA=±55°. IMAGES ON THE LEFT COLUMN HAVE POSITIVE FZA; E.G. THE IMAGE IN THE BOTTOM LEFT CORNER IS THE SAN ROSSORE VIEW OBTAINED WITH FZA=+55°.

We have estimated the atmospheric optical depth for 12 CHRIS spectral channels (Moshkov et al. 2009),

without applying compensation for the adjacency effect. The optical depth estimation procedure consisted of two phases: co-registration of the five images constituting the dataset, and the procedure of the optical depth estimation discussed above.

In the co-registration phase we have adopted the affine transformation shown in the following equations:

$$\begin{cases} x' = ax + by + c \\ y' = dx + ey + f \end{cases}$$

Here  $x$  and  $y$  are the coordinates of a pixel in the first image, and  $x'$  and  $y'$  are those in the second one. Coordinates are, as usual, column and row indexes ( $x, y$ ), as measured from the top left corner of each image. In order to find the coefficients in (18), some Ground Control Points (GCPs) have been visually chosen in both images, and their coordinates employed to calculate the optimal transformation connecting the two maps (we used eight points spread over the entire image). This yields an over-determined system of 16 equations with only six unknowns whose solution can be inferred by the least-squares method. With this procedure we have found the transformation coefficients ( $a, b, \dots, f$ ) from the nadir image to each of the four slant path images completing the dataset. The least squares minimization has been iterated in order to increase the precision of the co-registration phase. The accuracy of the determination of the transformation coefficients has been assessed as the r.m.s. distance between measured and predicted GCP coordinates.

The structure of our algorithm for  $\tau$  estimation reminds the moving window procedure often adopted for processing digital images. Our algorithm can be applied to monochromatic multi-angular datasets, meaning that multiple band datasets are processed sequentially iterating the algorithm for each spectral channel. The sequence of operations constituting the application of the algorithm to a single spectral band of a multi-angular dataset are depicted in the following. A square window, with size  $N_{fr}$  pixel, is adopted for scanning the available nadir image, with unit step along both axes. Window sizes in the range from 84 pixels up to 116 pixels have been attempted. The scanning procedure of a monochromatic image incorporates the following operations.

1. Extracting from any image of the multi-angular set the sub images corresponding to the current position of the moving window. This operation

utilizes the affine transformation in (18) with the free parameters previously determined in the co-registration phase.

2. Computing the variance in each multi-angular view of pixels conjugated to positions inside the moving window.
3. Estimating the optical depth  $\hat{\tau}(g_j)$  for any available observation angle (12), the optimal optical depth  $\hat{\tau}_m$  (15), the corresponding discrepancy  $\hat{\epsilon}$  (16), and discrepancy of means  $\hat{\epsilon}_p$  (17).
4. Steps from 1 to 3 are iterated after changing the position of the moving window. To reduce the computation burden we employed an empirical variance threshold  $\sigma_0$  in order to prevent the optical depth calculation over image fragments of lesser dispersion (which would produce lower quality optical depth estimates). At the completion of the scanning process associated to a given window size, the optical depth estimation  $\hat{\tau}_{ml}$  corresponding to the minimal discrepancy  $\hat{\epsilon}_l = \min\{\hat{\epsilon}\}$  is retained together with the discrepancy  $\hat{\epsilon}_l$  itself, and the discrepancy of means  $\hat{\epsilon}_{pl}$ .
5. Once the image scanning is completed, the entire procedure, steps from 1 to 4, is repeated using a larger moving window size. Window size has increased with a step of 4 pixels.

This originates nine optimal estimates  $\hat{\tau}_{ml}$ , nine minimal discrepancies  $\hat{\epsilon}_l$ , and nine discrepancies of means  $\hat{\epsilon}_{pl}$ , each one connected to the nine admitted sizes of the moving window. Among them we select as the best estimate  $\hat{\tau}_{mm}$  of the optical depth that optimal estimate  $\hat{\tau}_{ml}$  corresponding to the minimal discrepancy of means  $\hat{\epsilon}_{pl}$ , as shown by the next equation:

$$\hat{\tau}_{mm} = \min_{\hat{\epsilon}_{pl}} \{\hat{\tau}_{ml}, l = 1, \dots, 9\}$$

The optical depth estimates  $\hat{\tau}_{mm}$  and the corresponding values of the direct transmittance  $T = e^{-\hat{\tau}_{mm}}$  obtained from the CHRIS-PROBA images in 12 spectral channels are detailed in Table I. The corresponding atmospheric direct transmittance simulated for the same twelve spectral channels by means of the MODTRAN 5.2 (Anderson et al. 1995)

code are plotted in Fig. 2 together with the transmittance estimates. Simulations have been executed for the Mid-latitude summer model, utilizing four different aerosol conditions: 1) rural, with visibility of 23 km, 2) marine aerosol with 23 km of visibility, 3) rural aerosol and visibility of 5 km, and 4) urban aerosol with 5 km of visibility. Optical depth estimation in the last six spectral channels gave evidently wrong results, presumably due to the ascertained degradation of the sensor's radiometric response affecting these bands, see Barducci et al. (2009) and Cutter (2004). Let us note that the peak and the average Signal-to-Noise Ratio (SNR) typical of CHRIS-PROBA datasets decrease with increasing the wavelength (Barducci et al. 2005), giving rise to an additional possible reason for explaining the poor estimations obtained in the near infrared bands.

TABLE I OPTICAL DEPTH ESTIMATION FROM CHRIS-PROBA IMAGES

$N_{ch}$	$\lambda_{mid}$ (nm)	$\hat{\tau}_{mm}$	$\hat{T}$	$T$ (Modtran, 15 km visibility)
1	489.2	0.736	0.479	0.498
2	551.2	0.594	0.552	0.549
3	631.2	0.516	0.597	0.602
4	671.7	0.473	0.623	0.653
5	679.9	0.452	0.636	0.659
6	685.6	0.459	0.632	0.628
7	691.3	0.468	0.626	0.607
8	697.2	0.420	0.657	0.642
9	703.2	0.396	0.673	0.634
10	709.3	0.362	0.696	0.661
11	715.5	0.397	0.672	0.621
12	734.9	0.302	0.739	0.649

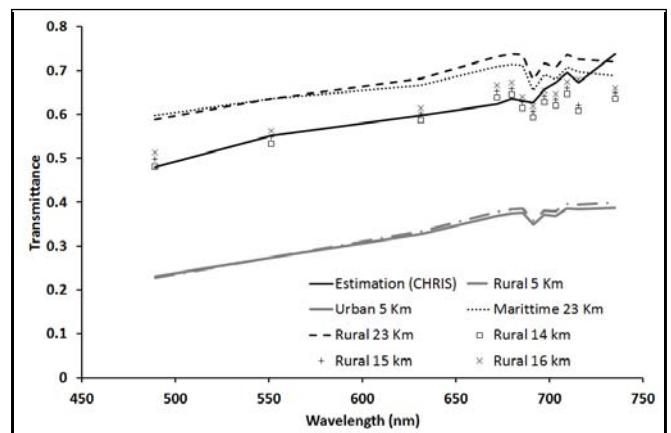


FIG. 2 EXAMPLE OF ATMOSPHERIC OPTICAL DEPTH ESTIMATION FROM CHRIS-PROBA DATA, AND ITS COMPARISON WITH SEVERAL MODTRAN 5.2 SIMULATIONS CALCULATED FOR VARIOUS ATMOSPHERIC MODELS AND SEVERAL VISIBILITY VALUES.

As can be seen the estimates compare fairly with the simulations, reproducing a similar amplitude and spectral distribution. The transmittance estimates deduced from CHRIS-PROBA data nearly approximate the Modtran 5.2 simulations with 15 km of visibility, as can be seen in Fig. 2 and Table I.

## Conclusion

The Earth's atmosphere heavily affects the remote sensing images acquired by spaceborne passive optical sensors due to radiation-matter interaction phenomena like radiation absorption and scattering. One of such phenomena is the direct attenuation of radiation reflected from the Earth's surface when it's passing through the atmosphere. The attenuation is characterized by the optical depth, which in turn determines the direct transmittance of the atmosphere.

In this paper we have suggested a new method for estimating the atmospheric optical depth stemming from multiangle remotely sensed images, not using any in-field measurement or external information about the atmosphere and the Earth's surface. We have reviewed possible errors affecting the optical depth estimations obtained with this method. The realization of this method permitted us to estimate the optical depth (direct transmittance) for twelve spectral channels of a data volume gathered by the imaging spectrometer CHRIS-PROBA. Estimations as far obtained compare fairly with optical depth simulations computed by the MODTRAN 5.2 code, especially for the first CHRIS-PROBA spectral channels.

We remark that optical depth values directly extracted from remotely sensed hyperspectral and multiangular images are a supplementary source of information concerning the state of the atmosphere. Potentially, the availability of such estimations fills the gap between the data acquisition and their utilization, permitting us to mitigate the complexity that hinders the generation of high-level remote sensing products. The assessment of high-level remote sensing products is often unmanageable due to the absence of validation and calibration in-field measurements, a shortage that is proficiently overcome by the discussed estimation algorithm.

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